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Laboratoire d'électromécanique et de machines électriques (LEME)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

MG Motor, Efficiency analysis with a dynamic simulation of the energy transfer.

Dr. C. Fleury, Prof. M. Jufer,

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Introduction

A study with the scaling laws has been made to evaluate the performances of the MG motor compared to standard BLDC motor. This approach was not suitable because the motor performances depends too much on the electronic behavior of the energy transfer.

The only way to correctly evaluate this motor was to modelize and simulate dynamically the high frequency energy transfer with the rectifying diode at the rotor level.

A simulation program has been developed and allows to calculate the torque and power balance in function of the spinning speed. By using this program, an efficiency of the MG motor limited to 50% in the best case has been noticed.

Reason of an efficiency limited to 50%.

A schematic of a rotor coil is presented in next figure. Two voltage supplies have been modeled:

- u_{iHF} = high frequency voltage induced in the rotor coil by the energy transfer
- $U_{imagnet}$ = back EMF voltage induced in the rotor coil by the stator magnets .

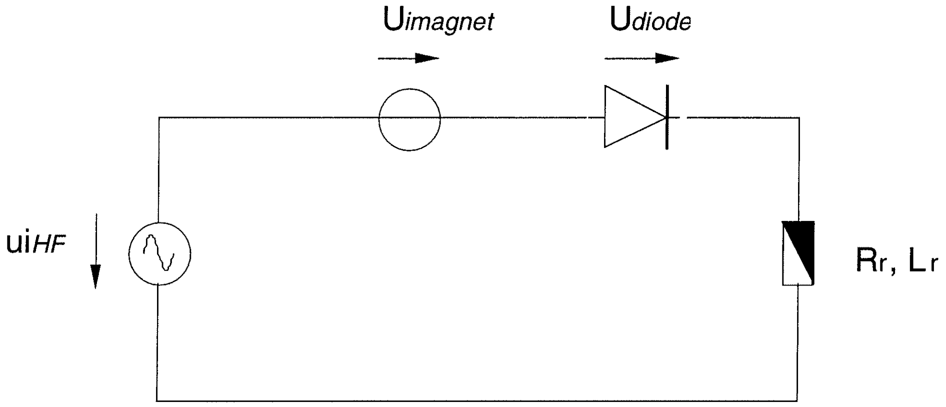

Fig. 1- Rotor coil model.

The dynamic simulation of this system has shown that if the spinning speed increases up to a value for which the magnitude of the $U_{imagnet}$ AC voltage (Fig. 5) becomes higher than the threshold voltage of the rectifying diode, a braking current appears in all rotor coils during a part of the negative half cycle of their $U_{imagnet\ BackEMF}$.
To avoid these braking currents, the magnitude of the Back EMF $U_{imagnet}$ has to be maintained just below the diode threshold voltage.
Then a high frequency voltage will be induced in the rotor coil only during a part of the positive half cycle of the Magnet BackEMF to produce a positive current (rectified as shown in Fig. 2 and 3), then a positive torque.

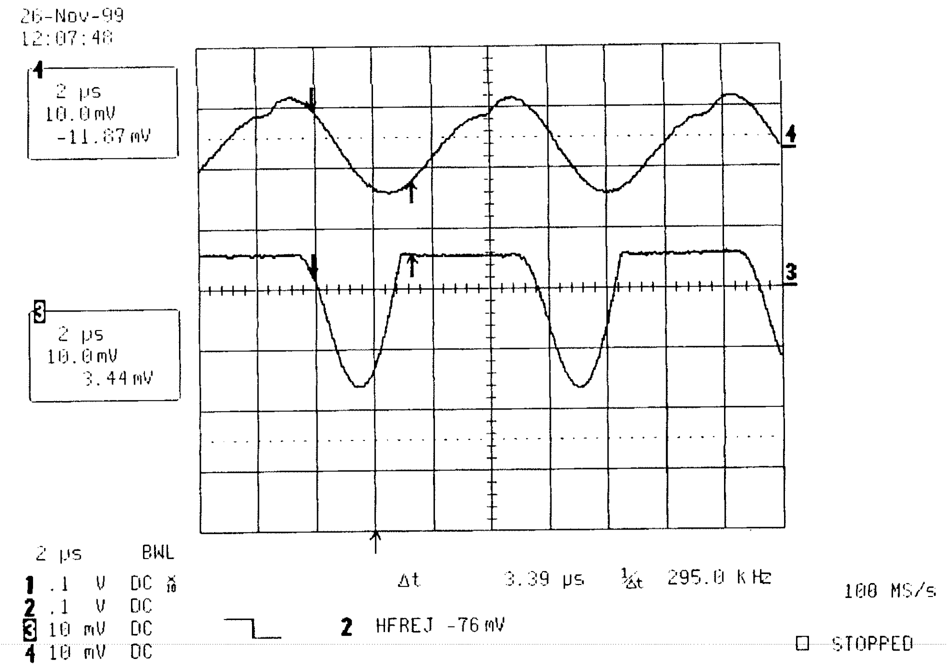

Fig. 2- Channel 4 excitation current, 2A/div - Channel 3 rotor current, 0.1A/div.

The product of the Back EMF by the high frequency current corresponds to the mechanical power produced by the rotor coil. This power is maximal when the Back EMF is maximal. Because the Back EMF magnitude is maintained at least below the diode threshold voltage, we can conclude that the power dissipated by the rectifying diodes will always be larger or equal to the mechanical power. Conclusion: even without taking into account the copper losses, the best efficiency that can be reached is 50% and it corresponds to a spinning speed for which the magnitude of the $U_{imagnet}$ AC voltage becomes equal to the threshold voltage of the rectifying diode.

Dynamic simulation of the system.

A realistic calculation of the MG motor efficiency has to take into account the power losses dissipated within the rectifying diodes in series with the rotor coils.
The transient evolution of the current induced by the high frequency energy transfer requires a dynamic simulation of the rotor coil model described in Fig. 1.
For this simulation, the rotor position and the value of the magnet Back EMF have been considered constant because the variation of the rotor position is slow compared to the high frequency (150kHz) of the sinusoidal voltage induced by the energy transfer (uiHF); for example, a spinning speed of 4500 rpm and p =3 corresponds to 225 Hz.

The system is then simulated for one rotor position and one spinning speed , to which correspond:

- a magnitude of the sinusoidal voltage uiHF;
- an equivalent dc value of the magnet Back EMF Uimagnet for the considered position;

As described in Fig. 3, the sinusoidal voltage uiHF and the resulting DC voltage Udc (composed by the diode threshold voltage and the Back EMF value for this position) are involved in the model.

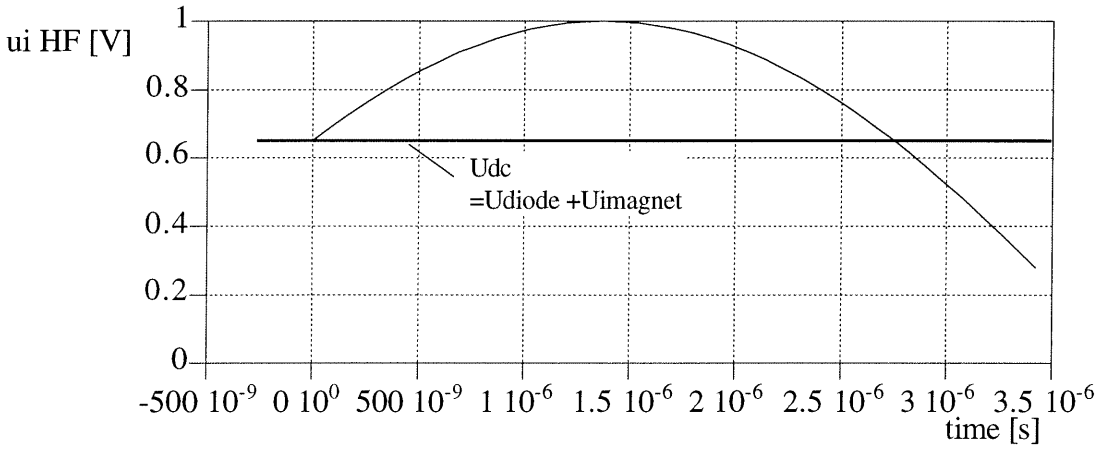

Fig.3-High frequency energy transfer compared to the resulting DC voltage .

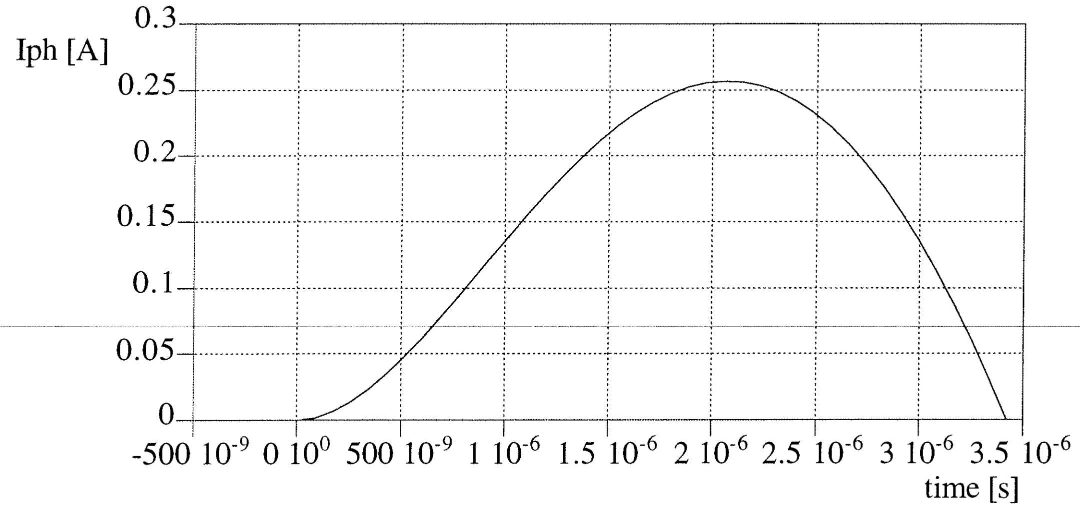

Fig. 4 HF induced current.

The diode starts conducting (Fig. 4) as soon as uiHF becomes higher than the resulting dc voltage Udc. Then, due to the inductance effect, the zero crossing of the HF current is delayed from the instant when uiHF passes again below Udc.

The dynamic simulation allows to calculate the transient evolution of the high frequency rotor current (Fig. 4) and its general shape corresponds to the measurements (Fig. 2).

The calculation of the efficiency requires the calculation of the various power acting in the system:

- $P_{copper} = R_r \cdot I_{RMS}^2$ copper losses in one rotor coil.
- $P_{diode} = U_{diode} \cdot \bar{I}$ power losses dissipated in the diode.
- $P_{elmagn} = U_{imagnet} \cdot \bar{I}$ electromagnetic power generated by one rotor coil.

Where:

- $I_{RMS} = f \cdot \sqrt{\int_0^{\frac{1}{f}} i^2 \cdot dt}$ is the RMS value of the current in one rotor coil calculated on one electrical period of uiHF (f = frequency of uiHF).
- $\bar{I} = f \cdot \int_0^{\frac{1}{f}} i \cdot dt$ is the average value of the current in one rotor coil.

The torque generated by one rotor coil is given by:

- $T = \dfrac{\bar{I} \cdot U_{imagnet}}{\Omega}$ is the average value of the torque over one electrical period.

For one spinning speed, calculation the torque in function of the rotor position.

As the rotor position changes (Fig. 5), the equivalent dc value of the back EMF $U_{imagnet}$ changes, as well as the magnitude of the high frequency voltage $u_{iHF} = U_{iHF} \cdot \sin(2\pi \cdot f)$.

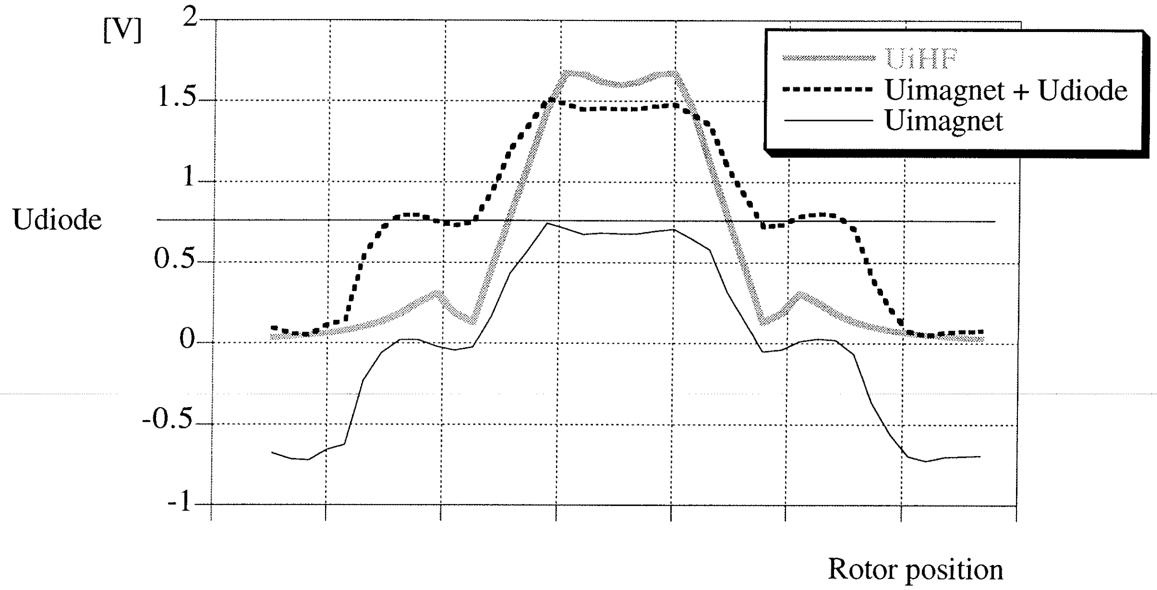

Fig.5 High frequency induced voltage compared to Magnet Back EMF + diode threshold voltage.

The high frequency current circulates in the rotor coil only for the positions corresponding to a magnitude of u_{iHF} higher than the sum of $U_{imagnet}$ and U_{diode} (Fig. 6).

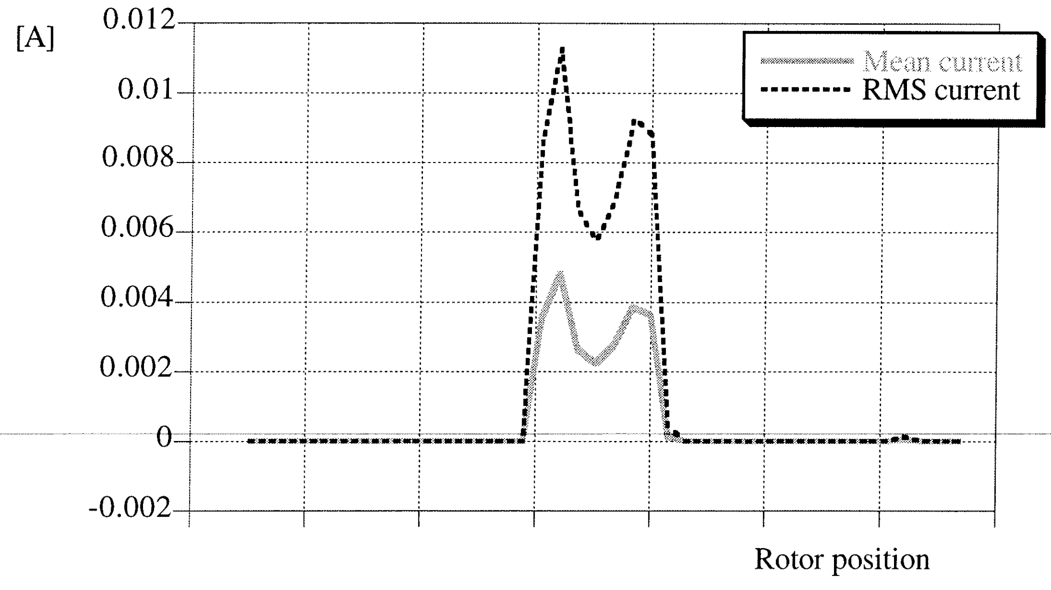

Fig.6 RMS and mean values of the HF induced current in function of the rotor position.

The average value of the torque generated by one coil can also be calculated if function of the rotor position (Fig. 7).

Mean value of the torque in function of the rotor position.

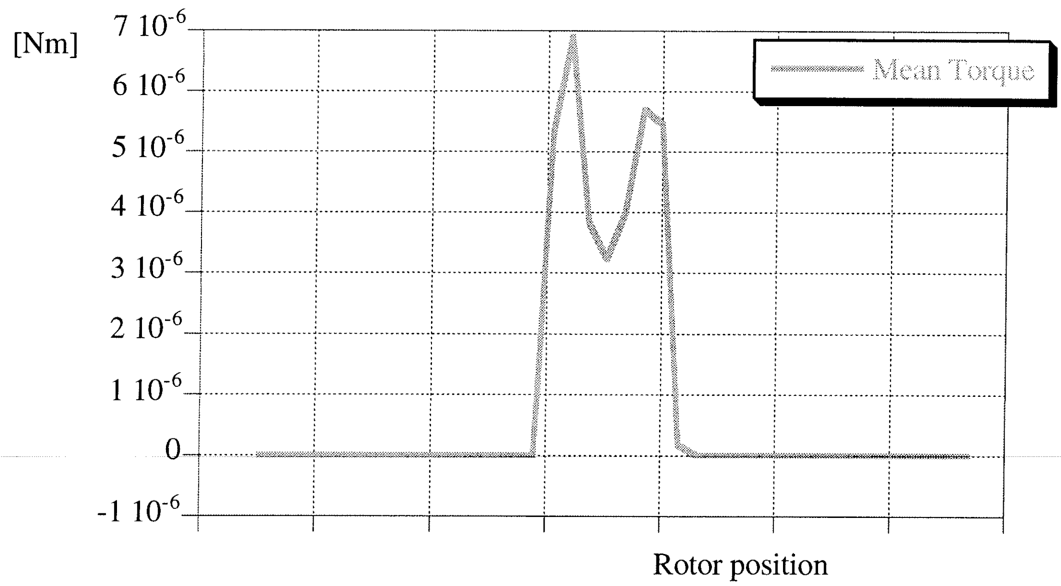

Fig.7

The simulation program also calculates the power losses and the electromechanical power in function of the rotor position.

Torque speed characteristic.

To evaluate the performances of the MG motor, average values of the torque and powers have to be calculated over one electrical period of the Magnet Back EMF. Then in function of the motor configuration (number of rotor coils Z and number of pair of poles p), the total motor torque can be calculated for one speed.

With an iteration over the speed, the torque speed characteristics is calculated.

For example, for $p = 3$, $Z = 9$ rotor coils, Udiode = 0.9V, Rr = 0.01 ohm

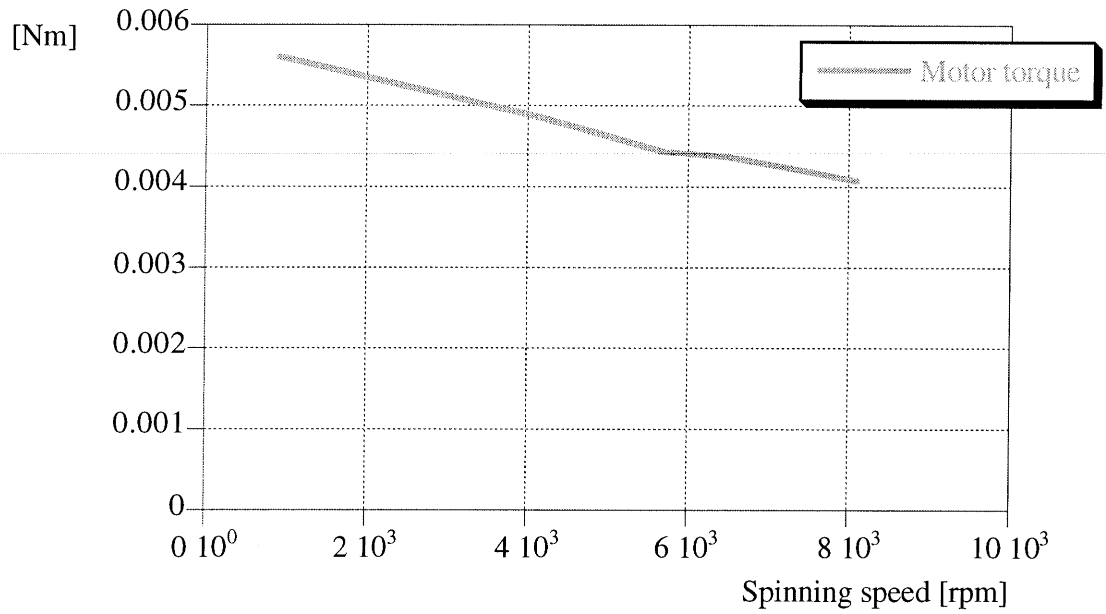

Fig.7 Torque speed characteristic

The power balance is presented in Fig. 8. The power dissipated in the diode remains higher than the generated electromagnetic power for almost the complete speed range, which means an efficiency below 50% (Fig. 9).

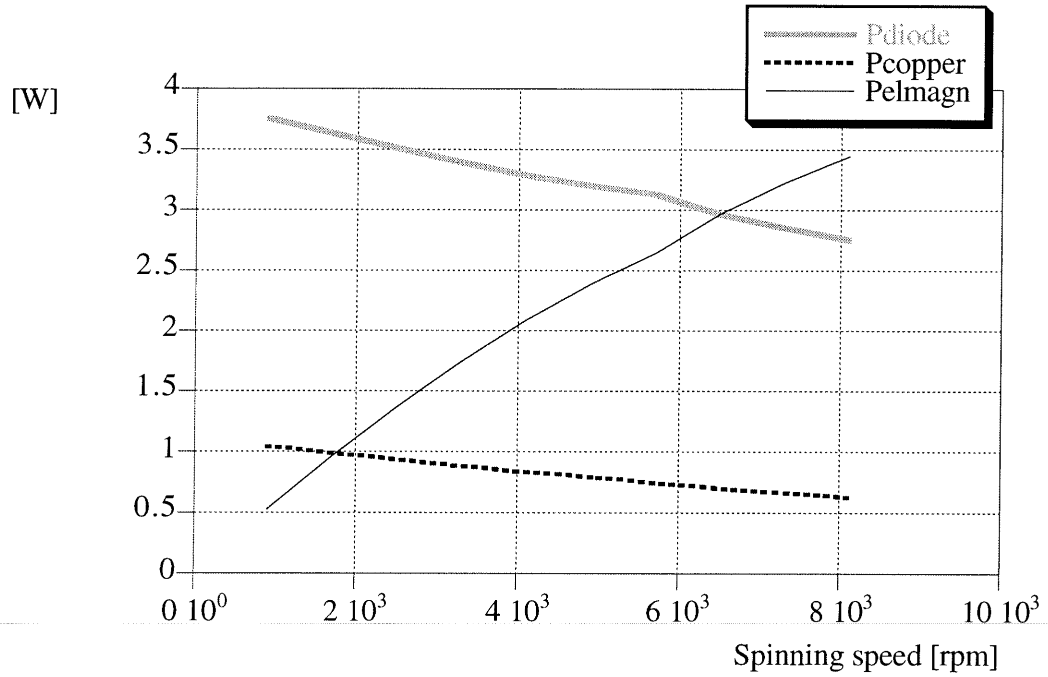

Fig.8 Power balance in function of the speed.

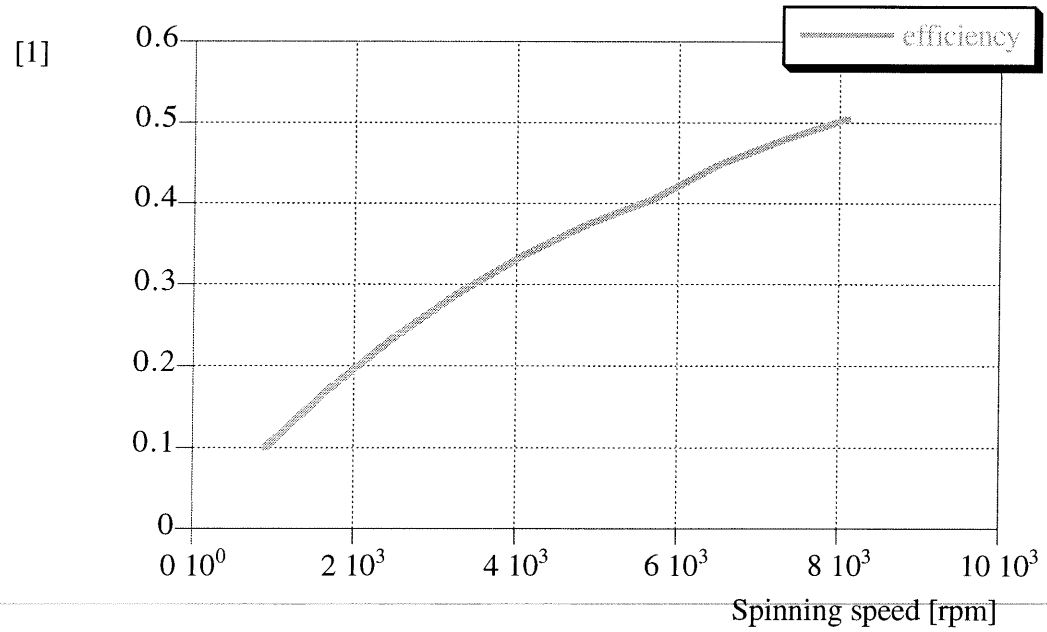

Fig.9 efficiency in function of the speed.

While the speed keeps increasing, the efficiency improves. This means that the Back EMF magnitude becomes close or higher than the diode threshold voltage. This improvement can not be achieved in practice.

The simulation program separately calculates the braking currents occurring during the part of the negative half cycle of the Back EMF for which the Back EMF is higher than the threshold voltage.
When the motor torque (due to the HF energy transfer) is combined with the torque of the diode braking currents, the resulting torque speed characteristic decreases quickly to zero as soon as the Back EMF magnitude becomes higher than the diode threshold voltage(Fig. 10).

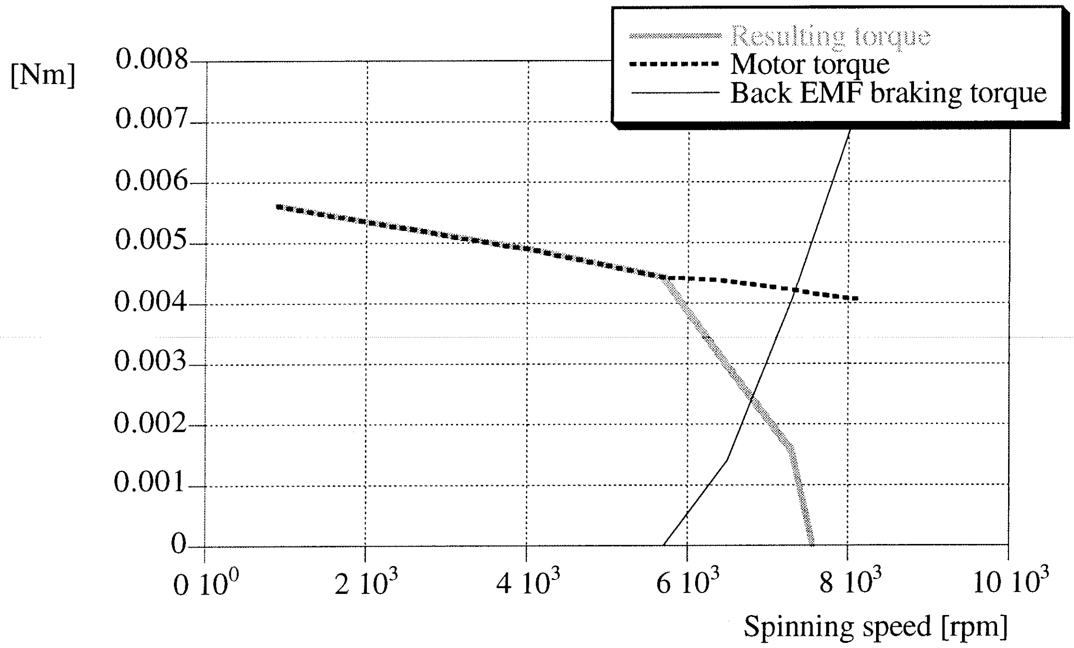

Fig.10 Real torque speed characteristic

Two parameters can be adjusted to increase the maximal speed of the MG motor:

- increasing the diode threshold voltage;
- decreasing the number of turn in series of the rotor coil.

For example, the simulated example can reach 5500 rpm for Udiode = 0.9 and a 10 turns in series per rotor coil. With 10 turns connected in parallel, the maximal spinning speed would increase to 55'000 rpm.

Conclusion

The dynamic simulation program developed during these last 3 month allows to calculate the torque speed characteristic of the MG motor.

From such characteristic, it is possible to point out new important particularities of this motor:

- the MG motor can reach high speed if the number of rotor turns in series is decreased and if the diode threshold voltage is increased;
- the efficiency of the motor is limited to 50%, which is quite low compared to standard BLDC motor.

The application field of such a motor will then be limited to applications fro which the efficiency is not an issue. But even if the energy consumption is not a concern, the global size and weight of a MG motor will always be larger than a standard BLDC motor, considering that for a similar temperature rise, the volume will have to be increased if the power losses dissipated in the system are higher.